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ATMOSPHERIC EFFECTS ON AIRBORNE LASERS FOR TACTICAL MISSILE DEFENSE: CLOUDS AND TURBULENCE

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In the context of Tactical Missile Defense (TMD), an Airborne (High-Energy) Laser (ABL) is investigated for its possible utility for boost-phase kill of a tactical ballistic missile, at a range of 100-1,000 km. Here we examine the effects of clouds and atmospheric turbulence, including possible compensation by Adaptive Optics (AO) techniques, which can interfere with the functioning of this concept. To avoid the effect of clouds, the aircraft carrying the laser should fly as high as possible, preferably above the tropopause. At 15 km (49 kft) there will be no problem at mid- and high latitudes, but in the tropics conventional aircraft cannot fly high enough to avoid possible interference from towering cumulonimbus, which have been found upon occasion as high as 20 km. Regarding the effects of atmospheric turbulence on beam propagation, if the airplane flies high enough that the optical viewing path avoids cloud, there would probably be no major problems with turbulence at ranges of not more than 100 km. However, for longer ranges, there may be significant effects of phase coherence, beam wander, and beam broadening that could require compensation by AO. There are critical uncertainties in models of atmospheric turbulence, suggesting that more data are needed. Work at USAF/Phillips Laboratory and at MIT/Lincoln Laboratory is attacking the problems of appropriate compensation for atmospheric turbulence by AO techniques, but the current level of effort is not adequate to support deployment of an ABL system for TMD on a near-term basis.

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ABSTRACT

In the context of Tactical Missile Defense (TMD), an Airborne (High-Energy) Laser (ABL) is being investigated for its possible utility for boost-phase kill of a tactical ballistic missile, at a range of 100-1,000 km. The propagation of the laser beam through the atmosphere can be stopped by clouds and atmospheric turbulence. To avoid the effect of clouds, the aircraft carrying the laser should fly as high as possible, preferably above the tropopause where there are very few clouds. Normal aircraft flight altitudes should be adequate at mid- and high latitudes, but not in the tropics. Atmospheric turbulence is highly variable, but generally falls off with increasing altitude. If the airplane flies high enough to avoid clouds, it is probable that for ranges of 100 km or less the effects of turbulence are not serious. However, there exist no experimental data on laser beam propagation through long-range near-horizontal paths, and available models of atmospheric turbulence are inadequate. Theoretical analysis summarized here suggests that for ranges in excess of 100 km there may be significant effects that could require compensation by Adaptive Optics, explicitly deformable transmitter mirrors. There are critical uncertainties in models of atmospheric turbulence, suggesting that experimental flight data are needed. Current work is attacking the problems of appropriate compensation for atmospheric turbulence by Adaptive Optics techniques, but the level of effort is not adequate to support deployment of an ABL system for TMD on a near-term basis.

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SUMMARY

The effectiveness of an optical laser weapon depends, in large part, on the characteristics of the optical path the beam must traverse. Among the factors influencing that path for airborne lasers intended to engage tactical ballistic missiles are clouds and turbulence.

In the context of Tactical Missile Defense (TMD), an Airborne (High-Energy) Laser (ABL) is examined for its possible utility for boost-phase kill of a tactical ballistic missile, at a range of 100-1000 km. Figure S-1 sketches the problem addressed, and Table S-1 outlines environmental issues. Here we examine the effects of clouds and of atmospheric turbulence--including its possible compensation by Adaptive Optical (AO) techniques with a deformable transmitter mirror--that can interfere with the functioning of this concept.

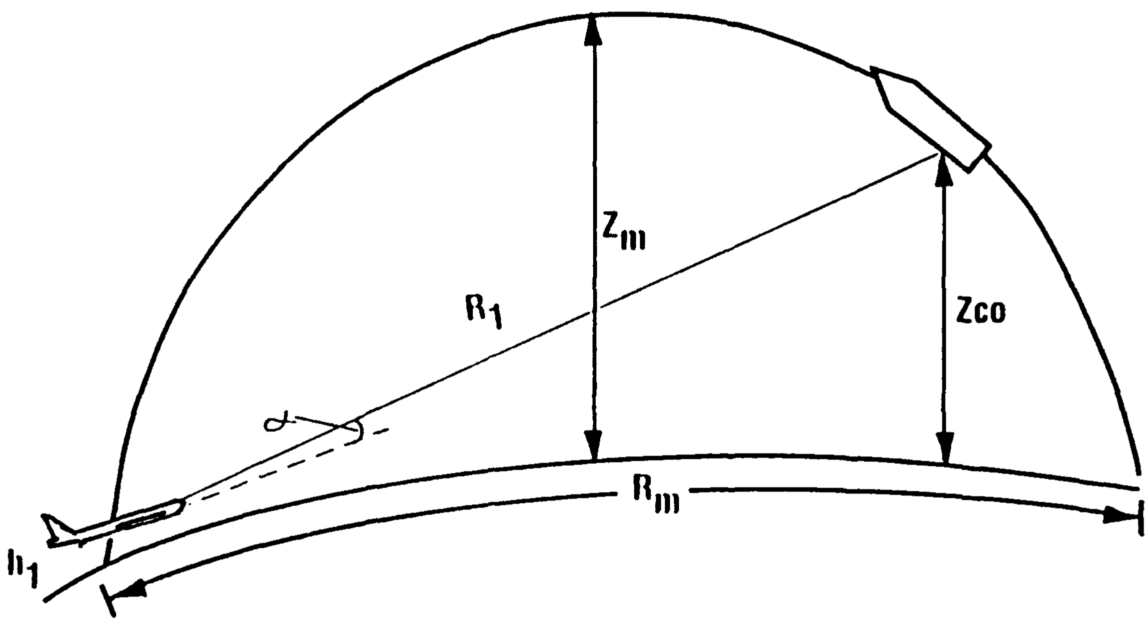

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Figure S-1. The Problem Addressed

Table S-1. Environmental Issues for Airborne Lasers

CLOUDS OCCUR FREQUENTLY

- May go up to tropopause
- High-altitude clouds are *cirrus* (optically thin in vertical viewing, horizontally flattened, may be optically thick in horizontal viewing) or *cumulonimbus* (thunderclouds: optically thick, convective; short-lived, but generate cirrus).

TROPOPAUSE HEIGHT varies with latitude and season (heights in km):

		January	July
Tropics	(10-30°N)	17	15.5
Midlatitude	(40-50°N)	10	13
Arctic	(60-80°N)	8.5	9.5

- "Normal" aircraft can operate up to 13.7 km (45 kft) which is above the tropopause (and above most clouds) at mid- and high latitudes, but not in the tropics where towering cumulonimbus may reach up to 20 km (66 kft).

TURBULENCE INCLUDING COMPENSATION BY ADAPTIVE OPTICAL (AO) TECHNIQUES

- Optical turbulence models are inadequate for long-range horizontal paths; more data needed.
- 100 km range--compensation problems due to adaptive optical bandwidth and spatial difference between probing and weapon beams.
- 500 km range--additional problems: existing theory fails due to strong fluctuations; saturation of scintillations and beam breakup; spot size and beam wander of several meters.
- AO compensation may not be required for ranges < 100 km (and some models suggest AO is not needed).
- Current work at USAF/Phillips Laboratory and MIT/Lincoln Laboratory on AO techniques is addressing these problems.

Clouds tend to occlude the optical path, and, therefore, limit both the geometries which are most likely to be favorable and the times and places at which lasers can be used effectively. At present, there are no known means to overcome the problems presented by clouds. This report gives some information as to how serious a problem clouds may be.

To avoid the effect of clouds, the aircraft carrying the laser should fly as high as possible, preferably above the tropopause.[1] At 15 km (49 kft) there will be no problem at mid- and high latitudes, but in the tropics conventional aircraft cannot fly high enough to avoid possible interference from towering cumulonimbus[2] (tropical thunderstorms), which have been found upon occasion as high as 20 km.

Turbulence tends to introduce perturbations in the optical path. Adaptive optics offer a possible solution to this limitation. However, the design and development of appropriate adaptive optics depend strongly upon our ability to characterize the perturbations to which the optics must adapt. This report examines some of the mechanisms by which turbulence introduces perturbations in an effort to delineate the requirements for adaptive optics. We find that such data as has been collected has focused primarily on the vertical paths common to astronomical observations and is both incomplete and not directly applicable to the near horizontal paths of airborne anti-ballistic missile laser weapons.

Atmospheric turbulence is a complex, intermittent, and highly variable phenomenon, but generally falls off with increasing altitude. Figure S-2 shows the parameter C_n^2 [3] which gives a measure of the intensity of turbulence and demonstrates the large amount of small-scale horizontally stratified structure superposed on a general decline with increasing altitude. However, to date most work on the effects of turbulence on light propagation through the atmosphere has focused on near-vertical paths, mainly for application to "astronomical seeing through the atmosphere" and the twinkling of stars. Thus there exist no experimental data of the effect of atmospheric turbulence on near-horizontal laser beam propagation at flight altitudes for ranges greater than a few kilometers.[4]

Regarding the effects of atmospheric turbulence on beam propagation, if the airplane flies high enough for the optical viewing path to avoid cloud, there would probably

---

1 The tropopause defines the boundary between the troposphere (below) and the stratosphere (above). Weather effects, including clouds, are almost always confined to the troposphere.

2 Thunderclouds of large vertical extent due to solar forcing. They are common at relatively low latitudes, and occur frequently during the early afternoon.

3 C_n^2 is defined in Section 3.2, below.

4 A substantial effort (probably using two aircraft, or an aircraft and a balloon-mounted reflector) would be required to obtain the large amounts of data that are needed.

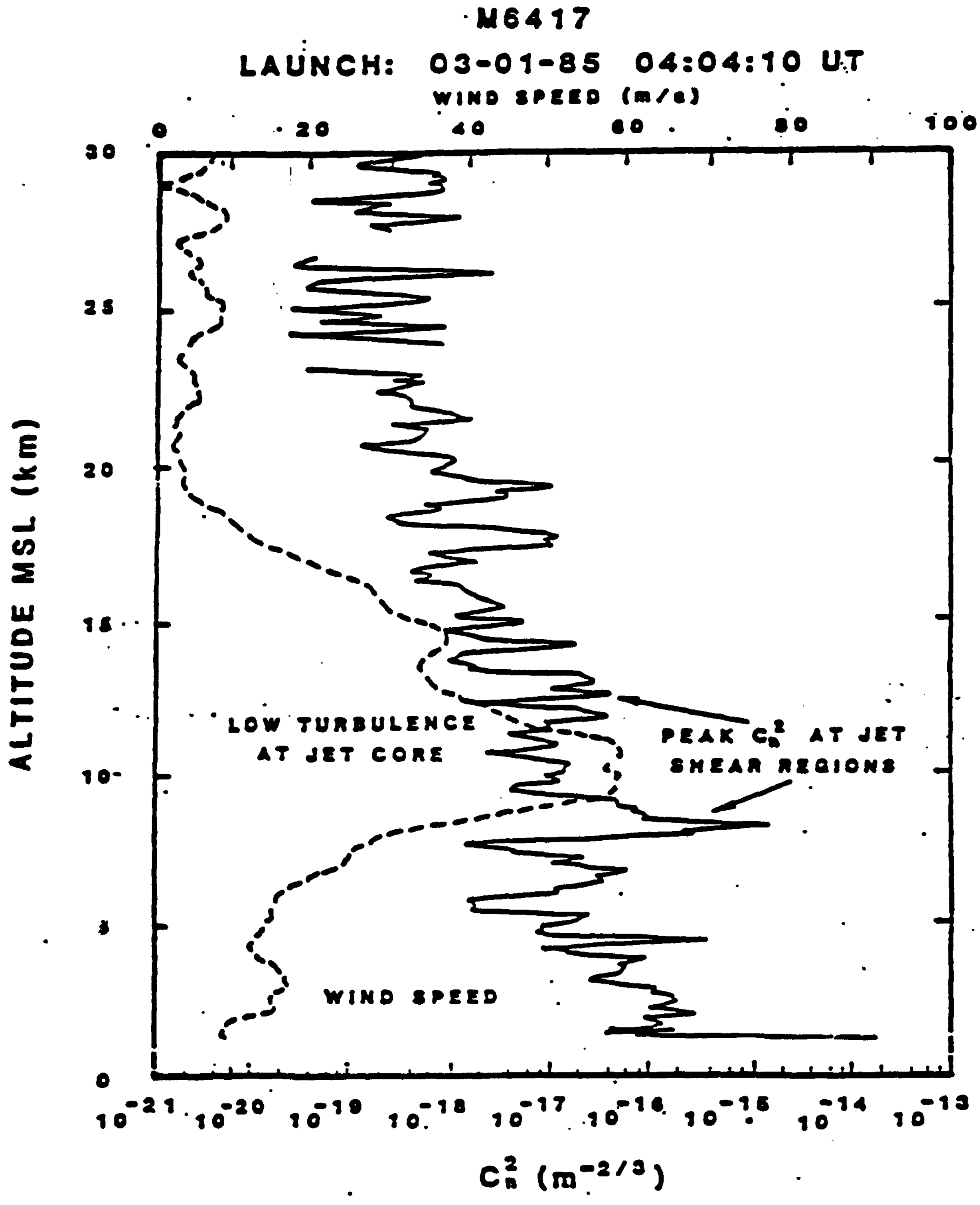

Figure S-2. Optical Turbulence in the Atmosphere: Structure of the Parameter C_n^2. Note that while C_n^2 decreases generally with increasing altitude, it has a large amount of small-scale vertical structure. (Data provided by R.R. Beland, USAF-PL/GP)

be no major problems with turbulence for ranges of 100 km or less. However, for significantly longer ranges, there may be significant effects of phase coherence, beam wander, and beam broadening that may require compensation by AO. Normally such AO requires a beacon on a cooperative target, which would of course not be available in the situation discussed here. USAF Phillips Laboratory (Fugate, 1991; Gates and Ellerbroek, 1991) has suggested a potential correction method that involves transmitting an illuminator beam whose center is positioned just in front of the nose of the target to provide an aimpoint for the high-energy laser (HEL) beam. For related work at MIT/Lincoln Laboratory, see Primmerman et al., 1991, and work by J. Herrmann (MIT/Lincoln Laboratory) in progress.

The discussion of turbulence points to several questions and problems. With regard to effects of phase coherence, beam wander[5] and beam broadening,[6] it can be shown that for propagation along a 100-km path that has turbulence representative of 15-km altitude, the turbulence effects are of the same order as vertical propagation from ground to space, but longer paths are worse: for ranges of order 500 km or greater the transverse motion of the laser beam at the target due to turbulence is of order 1 meter or larger so that the beam cannot be kept on the target. For scintillation[7] and departure from isoplanatism, a near-horizontal path of 100-km length is worse than a vertical ground-to-space path. Specifically, the long near-horizontal paths may violate the condition of weak fluctuations (defined in Section 3.5, below) that is assumed in deriving expressions for optical effects. There is no complete propagation theory for anything other than the weak fluctuation case. Additional questions and problems are raised in the specifications for adaptive optics, specifically the spatial difference between probing and weapon/power beams and the required bandwidth. These questions arise because of the variability of the atmosphere through which the beam is scanned at the high slew rates required to track a tactical missile defense (TMD) target, but because of these high slew rates, thermal blooming[8] of the beam will not be a problem.

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5 Discussed in Section 3.6

6 Discussed in Section 3.7

7 Time-dependent variations in refractive index due to turbulence leading to "twinkling" of the signal.

8 When beam energy is absorbed by the atmosphere, the air in the path gets heated and expands so that the beam is spread by refraction. This process is called *thermal blooming*. Current calculations by J. Herrmann (MIT/Lincoln Laboratory) find this process to be negligible--or at least quite correctable--for the present problem.

We conclude that:

- More information on clouds would be helpful in defining the operational limitations of an airborne anti-ballistic missile laser weapon.
- Data specific to the perturbations of horizontal optical paths in the atmosphere *must* be collected before one can undertake, with any degree of confidence, a design of adaptive optics necessary for the success of an airborne anti-ballistic missile laser weapon.

1. THE PROBLEM

An airborne High-Energy Laser (ABL) is considered for boost-phase kill of a tactical ballistic missile, at a range of 100-1000 km. Figure 1 sketches the problem addressed. An ABL flying at altitude h_1 attacks a missile in boost phase at altitude z_1, at range R_1, and the effective elevation angle of the laser beam is α. Table 1 lists representative booster cutoff heights, z_{co}, the apogee height z_m, and the corresponding value for α at booster cutoff for an aircraft located over the target at 15-km altitude, all as a function of missile range R_m.

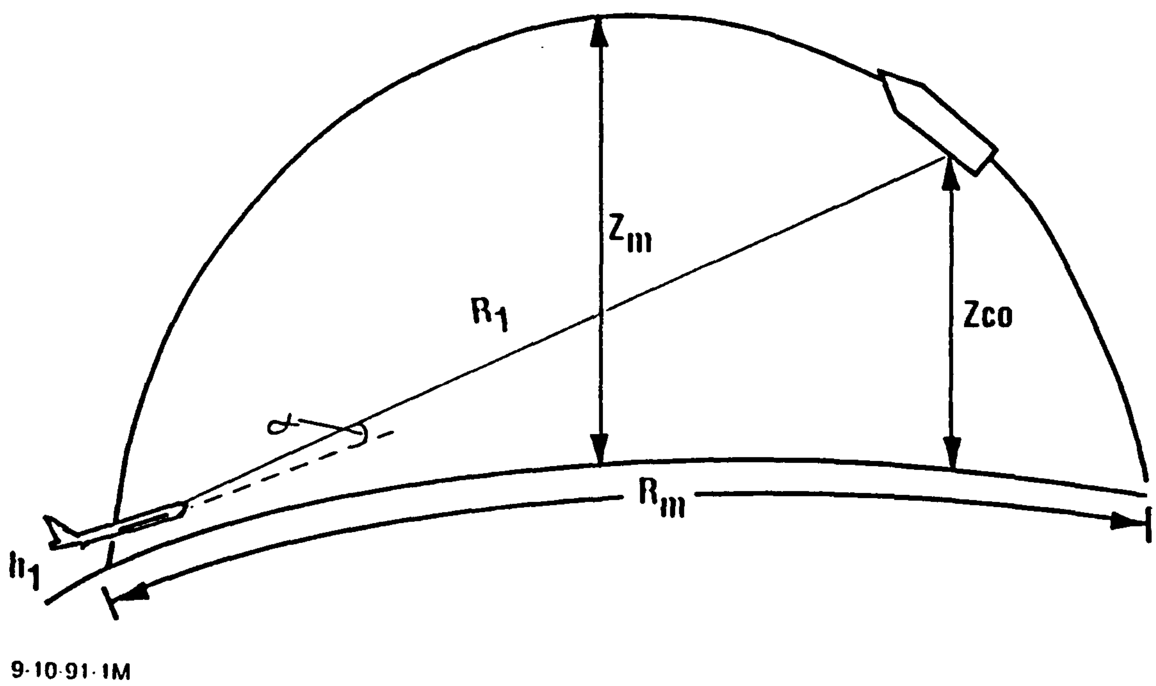

Figure 1. The Problem Addressed

Modern commercial subsonic aircraft are certificated to fly at altitudes up to 45 kft or 13.7 km; the B-52 bomber (which might be a surrogate platform for an ABL) can fly somewhat higher, while the Concorde supersonic transport and the U-2 high-altitude reconnaissance aircraft can fly up to 20 km and possibly higher.

Table 1. Some Representative Trajectory Data*

Range (km)	312	600	880	1500	3000
Apogee (km)	88	150	250	350	660
Booster Burnout Height (km)	29	37	56	97**	116
Velocity at Booster Burnout (km/sec)	1.6	2.2	2.7	3.4	4.5
Path Viewing Angle ($\alpha°$)	2.6	3.5	2.7	3.1	1.9

* Calculations of R.G. Finke, IDA, for "representative" ballistic missiles. The shorter range missiles are single-stage, while for 1,500-3,000 km, two-stage vehicles are considered. Note that a Scud-B fired at a range of 300 km burns out at 52-km altitude.

** Applies to second stage. First stage burns out at 24 km and velocity 1.8 km/sec.

Clouds and atmospheric turbulence can interfere with the functioning of the present concept.

Clouds occur almost exclusively in the *troposphere* which extends from the surface up to the tropopause: Table 2 gives mean seasonal heights of the *tropopause*. Above the troposphere lies the *stratosphere*, which has hardly any clouds except for some towering cumulonimbus[1] in the tropics. Figure 2 supplements Table 2 by showing the location of tropical, midlatitude, and polar tropopause in winter, and also the polar and subtropical jetstreams, regions near which turbulence frequently occurs.

Table 2. Mean Seasonal Heights of the Tropopause (Source: Jursa, 1985, p. 16-46)

	Altitude (km)			
Latitude (N)	Dec.-Feb.	May-May	June-Aug.	Sep.-Nov.
60°-80°	8.4	8.8	9.4	9.2
50°-60°	9.2	10.0	11.3	10.0
40°-50°	10.0	11.0	12.7	11.8
30°-40°	14.0	13.8	14.0	14.2
10°-30°	17.0	16.8	15.7	16.3

1 Thunderclouds of large vertical extent due to turbulence. They occur frequently during the early afternoon, and are particularly common at low latitudes.

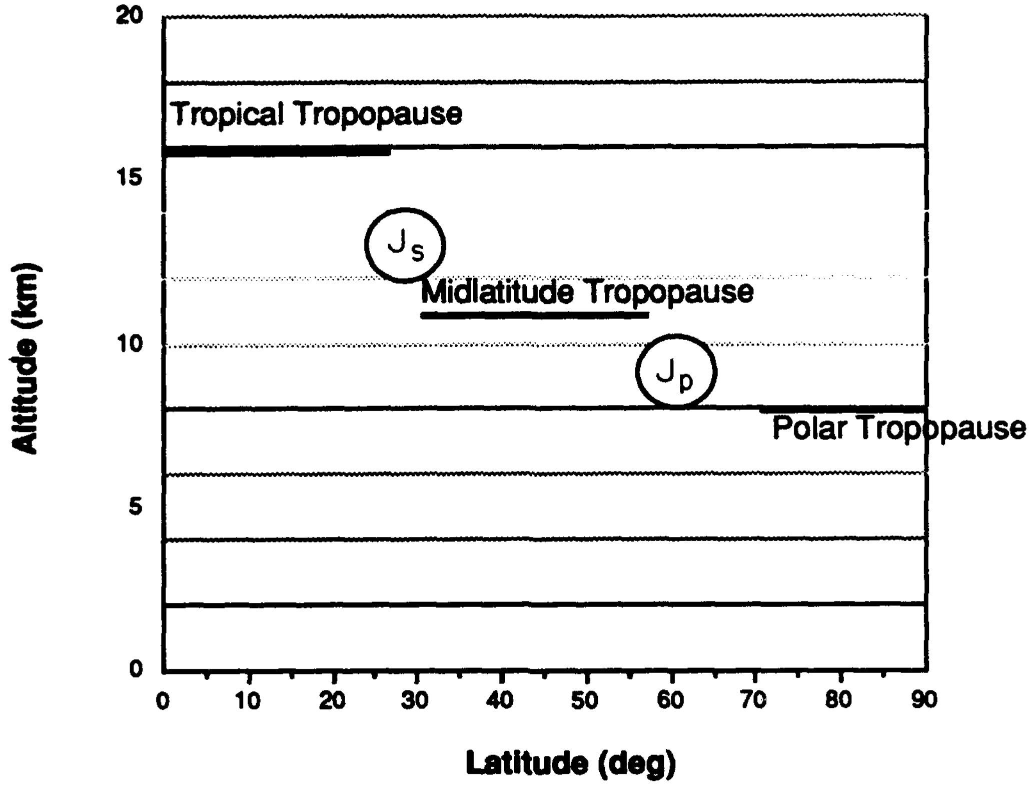

Figure 2. Schematic Location of Tropopause and Jet Streams (J_s = Subtropical Jet, J_p = Polar jet) in Winter

Atmospheric turbulence is a very complex and highly variable phenomenon, found in horizontal layers perhaps 100-1,000 m thick, whose intensity generally falls off with increasing altitude. Figure 3 gives a representative sketch of the parameter C_n^2, which is a measure of the effect of turbulence on optical propagation; C_n^2 is defined in Section 3.2, below. Note that this parameter falls off somewhat with increasing altitude, fluctuates by one to two orders of magnitude over vertical distances of order 100 m, and peaks near the jet stream boundaries or shear regions. Figure 4 supplements Figs. 2 and 3 by indicating the structure of the jetstreams, both for wind and for turbulence. Reference to Fig. 3 shows that a near-horizontal view path[2] will encounter more or less turbulence in the form of thin but highly turbulent "pancake" layers. If one ignores the effects of clouds and just

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[2] The angle α of Fig. 1 is less than 1-5 deg.

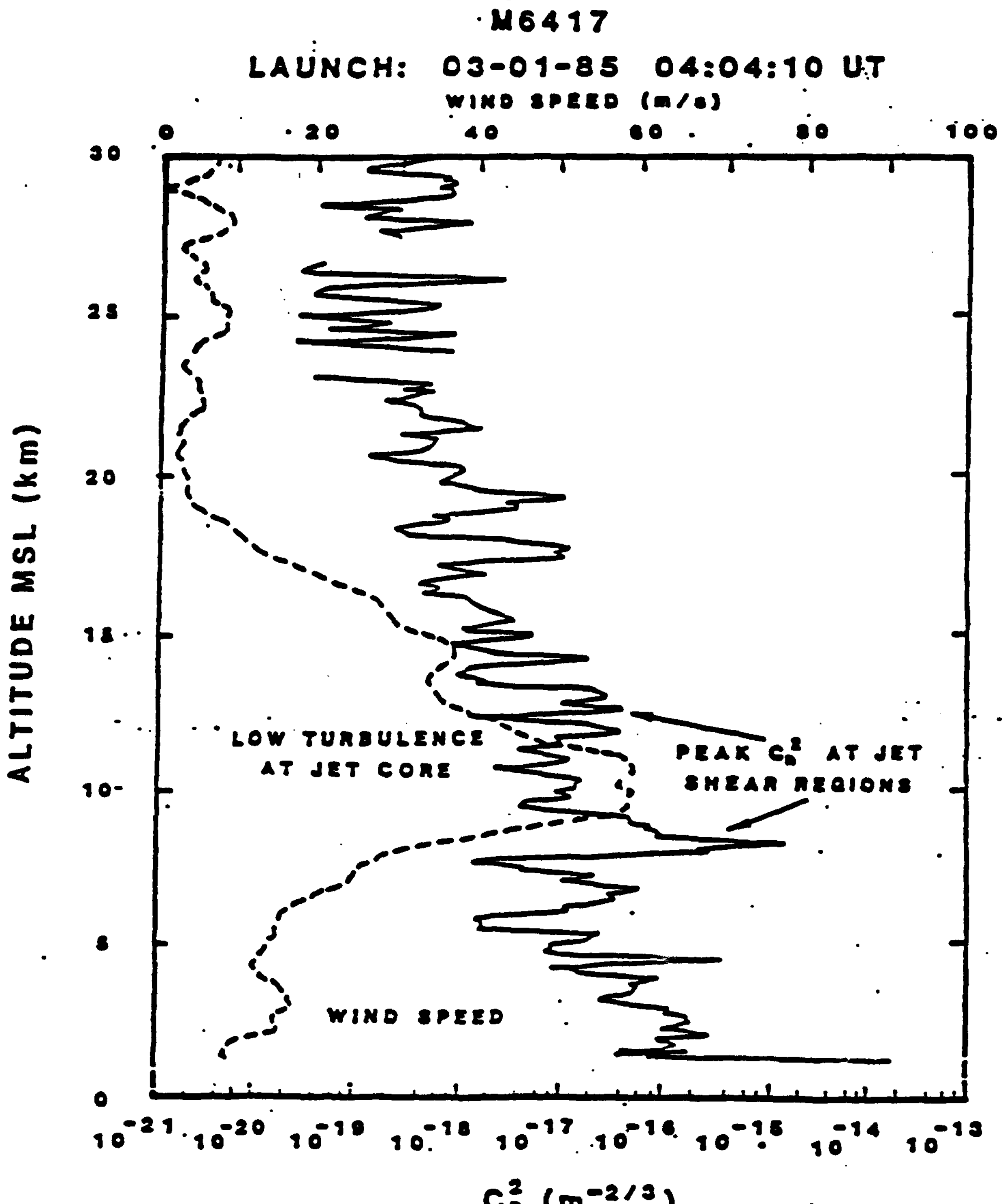
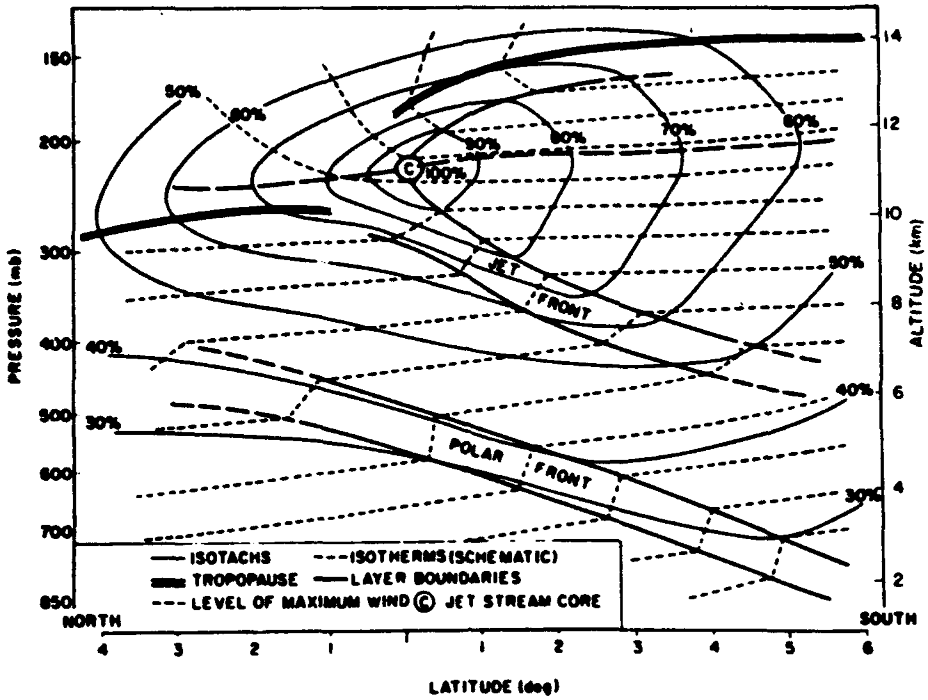
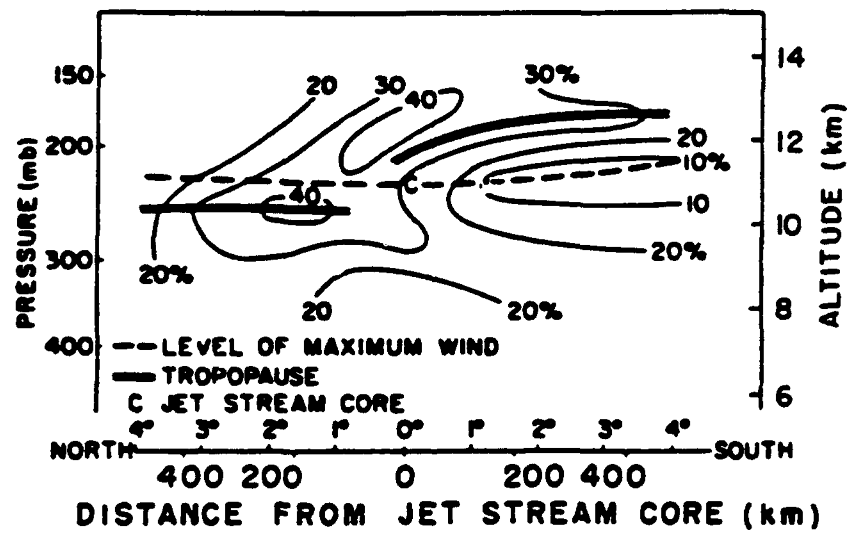


Figure 3. Optical Turbulence in the Atmosphere at Mid-Latitudes: Structure of the Parameter C_n^2 (defined in Section 3.2) and the Wind Speed.



(a) Idealized model of the jet stream, average structure in a cross-section perpendicular to the flow. (Percent of the core speed is given for each isotach; wind direction is into the page.)



(b) Turbulence in varous sectors of a typical jet stream cross section. [Frequency (%) of occurrence is shown for each contour.]

Figure 4. Models of the Jet Stream: Wind Speed and Turbulence (Source: Jursa, 1985, p. 17-28).

considers the effects of thin layers of turbulence, on account of the curvature of the earth the maximum path length in a layer of thickness d = 0.1 km is 36 km. Here the propagation in sight paths looking slightly upward from flight altitudes may be slightly degraded; paths that look downward into the relatively denser and more turbulent lower atmosphere are likely to give unacceptably poor propagation due to turbulence, even in the absence of clouds.

At 15 km (49 kft) clouds will be no problem at mid- and high latitudes; however, in the tropics, in particular in the Inter-Tropical Convergence Zone (ITCZ),[3] conventional aircraft cannot fly high enough to avoid possible interference with towering cumulus, which have been found upon occasion as high as 20 km.[4] Regarding the effects of atmospheric turbulence on beam propagation, provided the airplane flies high enough to avoid clouds, it would also avoid major problems with turbulence for paths of 100 km or less,[5] especially at longer wavelengths in the 0.5-10 μm range,[6] and if the minimum path viewing angle α is greater than 2-5 deg, that is if the target is not attacked at altitudes below about 30 km.

Assuming that an appropriate high-energy laser (HEL) can be built and operated, the principal atmospheric propagation-related problems with using a laser weapon in this way are the following:

1. Loss of beam integrity in going through the aircraft boundary layer.
2. Scattering (and absorption) of the beam by clouds between laser and target.
3. Degradation of beam by atmospheric turbulence between aircraft and target.
4. Compensation for turbulence effects by adaptive optics techniques.
5. Thermal blooming of the laser beam due to heating of the atmosphere by beam absorption--see Section 5.1.
6. Atmospheric ducting--see Section 5.2.

---

3 The Inter-Tropical Convergence Zone (ITCZ) is a region--typically near 5°N-25°N in summer and from 15°S to 5°N in winter--in which the solar-driven atmospheric "Hadley" circulation at low latitudes transports air upwards from the surface into the stratosphere. Thus it corresponds to a high effective tropopause, and has lots of convection with thunderclouds rising up to 20-km altitude.

4 Modern commercial long-range subsonic aircraft are certificated to fly at altitudes up to 45 kft or 13.7 km; the B-52 bomber can fly somewhat higher, while the Concorde supersonic transport and the U-2 reconnaissance aircraft can fly up to 20 km or possibly higher.

5 However, there will probably be significant problems at longer ranges.

6 In fact, the wavelengths considered here range from 1.06 to 3.8 μm.

Problem 1 will not be addressed here. It has been addressed in the AFWL Airborne Laser Lab (ALL) Program of the 1975-85 time frame, which showed that for the 10 μm spectral region (but not for the shorter wavelengths of interest for the current application) this problem is negligible. Much more work will be needed on this topic, whose results are highly airframe- and wavelength-dependent.

Problems 2, 3, and 4 are addressed in Sections 2, 3, and 4, respectively, and problems 5 and 6 are discussed in Section 5.

2. CLOUDS

Table 3 gives some representative data on the frequency of occurrence of clouds--both total and high-altitude clouds--at globally representative locations for both summer and winter conditions. Note that over most of the earth clouds occur very frequently, but in general by remaining above the tropopause (cf. Table 2) one can avoid them.

Table 4 gives more data on high-altitude (ice) clouds or cirrus, which normally occur below the tropopause and are frequently optically thin in vertical viewing. We also indicate subvisual cirrus, which are so thin that they are generally not seen in vertical viewing; however, in near-horizontal viewing they can be optically thick (for extinction = scattering + absorption), so that they can stop laser beam propagation.

Table 3. High and Total Cloudiness at Representative Locations in the Northern Hemisphere.
3DNEPH data from Malick and Allen (1978,1979)

Location	Coordinates		High/Total Cloudiness	
	Longitude	Latitude	January	July
China Lake, CA	36°N	117°W	.17/.38	.12/.18
Grand Forks, ND	48°N	95°W	.38/.63	.31/.56
Maui, HI	21°N	156°W	.14/.40	.12/.50
Hudson Bay	60°N	88°W	.06/.36	.08/.29
N. Atlantic S	52°N	35°W	.24/.81	.13/.70
N. Atlantic N	62°N	30°W	.18/.76	.16/.72
Jan Mayen Is.	71°N	10°W	.20/.81	.16/.85
Thule	76°N	68°W	.10/.35	.11/.73
Barrow, AK	71°N	156°W	.08/.34	.11/.64
Arabian Sea	8°N	65°E	.02/.23	.16/.55
Teheran	36°N	52°E	.14/.38	.02/.22
Ionian Sea	39°N	18°E	.07/.54	.01/.06
Moscow	56°N	39°E	.22/.61	.24/.46
Tyuratam	46°N	64°E	.16/.49	.13/.30
Lop Nor	40°N	91°E	.22/.48	.24/.57
Vladivostok	43°N	132°E	.11/.43	.22/.66
Japanese Trough	35°N	150°E	.16/.67	.12/.37
Anadyr	64°N	177°E	.28/.59	.21/.75
Murmansk	69°N	34°E	.22/.70	.16/.66

Notes:

a. High/total cloudiness means, for example, that at China Lake in January high clouds occur 0.17 of the time and total cloudiness occurs 0.38 of the time.

b. These data come largely from downward viewing satellites such as NOAA-6 and DMSP, which tend to *under-report* optically thin clouds.

c. Clouds are reported as present when at least 1/10 of the appropriate field of view is covered by clouds.

d. High clouds are those above 7 km, with the altitude determined by the effective radiative temperature in the 10- to 12-µm infrared band as compared with the atmospheric temperature/altitude profile.

e. High clouds are thus mainly moderately thick cirrus or cirrostratus, plus some cumulonimbus (thunderclouds) at the lower latitudes ($\lesssim 30°$).

Table 4. Global Frequency of Occurrence of Cirrus Clouds

Type of Observation	Tropical (ITCZ, 10° S to 20° N)	Mid-Latitude (30° to 45° N)		Subarctic (60° to 75° N)	
		Summer	Winter	Summer	Winter
A. Surface observations[1]	0.65	0.33	0.39	0.36	0.32
B. Surface observations, Row A corrected for low cloud cover[2]	0.80	0.40	0.50	0.45	0.40
C. USSR stations (land)[3]	-	0.30	0.48	0.55	0.59
D. Surface observations over the ocean[4]	0.37	0.34	0.27	0.44	0.35
E. Limb-viewing satellite data (SAGE):[5] Cirrus	0.40	0.44	0.34	0.46	-
Subvisual cirrus[6]	0.15	0.13	0.15	0.11	-

1 Data summarized by Hall et al. (1983) from Chang and Willand (1972) who used 10 surface stations.

2 From Hall et al. (1983) based on Chang and Willand (1972).

3 Izumi (1982): "Mid-Latitude" is average of Simferopol and Tashkent, "Subarctic" is average of Leningrad and Murmansk.

4 Hahn et al. (1982).

5 Woodbury and McCormick (1986); data for 34 months only, February 1979 to November 1981.

6 Subvisual cirrus is so thin that it is generally not seen in vertical viewing, but in near-horizontal viewing it can be optically thick.

3. ATMOSPHERIC TURBULENCE

3.1 INTRODUCTION AND OVERVIEW

The atmosphere is not a homogeneous medium. The density, temperature, pressure, and humidity fluctuate on a variety of space and time scales, and this leads to random variations in the index of refraction n(**r**,t) seen by a propagating electromagnetic wave. Explicitly, the flow becomes turbulent if the energy production due to wind shear is large compared to the buoyancy term in the equation of motion.

Atmospheric turbulence is a very complex and highly variable phenomenon. Figure 3 shows that in the atmosphere there are horizontal layers of strong turbulence perhaps 100-1000 m thick; atmospheric turbulence generally falls off somewhat with increasing altitude. Our current understanding of turbulence in general and of atmospheric turbulence in particular is somewhat limited. The "standard" models[7] assuming homogeneous and isotropic turbulence are surely not universally applicable, but such models are normally used in analyses of turbulence as the "best available" description. One characteristic of turbulence is that energy normally enters at large spatial scales, cascades down to smaller scales, and eventually gets dissipated into heat energy at very small scales. The "inertial range" of turbulence lies somewhere in this cascade where neither generation nor dissipation are important but the scale is sufficiently small so that the motion is largely isotropic (i.e., gravitational flattening of the "eddies" is unimportant). For an introductory discussion of atmospheric turbulence, see, e.g., Tennekes and Lumley, 1972.

The refractive index n in the atmosphere differs only very slightly from unity: a typical value at sea level is 1.0003, but fluctuations on the order of 1 percent in the 3×10^{-4} residual are sufficient limit astronomical and other "seeing" through the atmosphere and to produce beam wander, beam spread, and intensity fluctuations in a laser beam. These phenomena arise because of fluctuations in the residual, (n−1), due to atmospheric turbulence, which accumulate along an optical path in the atmosphere.

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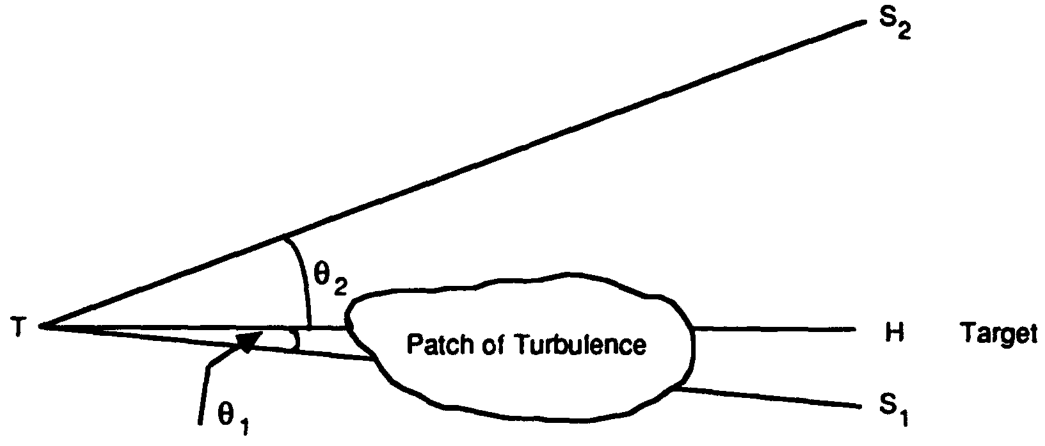
[7] Which are intended for near-vertical propagation.

In the past most interest has concerned vertical (or near-vertical) optical paths through the atmosphere, and because (n-1) is proportional to density ρ, existing models of optical turbulence (such as the SLC, HV 5/7 and AMOS models shown in Figs. 6 and 7) were designed for such near-vertical paths; thus, relatively small changes in these models can produce large effects for the present near-horizontal paths.

For laser propagation along a given path the effects of turbulence are characterized by three parameters: C_n^2 (defined in the following section 3.2) as a measure of the overall intensity of turbulence; *coherence length*[8] which gives an effective distance scale beyond which increasing the size of optics [explicitly, exit (lens) diameter D] does not increase the effective resolution; and the spatial (angular) difference between the probing and target laser beams, which is characterized by the *isoplanatic angle* θ_0 (as is indicated in Fig. 5) which is defined as follows. Two paths from source to target (e.g., at different times) are characterized by a difference in viewing angle. If the viewing angles for these two paths differ by more than the isoplanatic angle θ_0, the turbulence along the two paths will be significantly different, so that the results from one of these two paths cannot be used to correct for turbulence along the other one. The condition of isoplanatism corresponds to two (or more) paths so similar to one another that the results along one path can be used to correct (adaptively) for the other paths. Figure 5 sketches how the condition of isoplanatism can be used for the adaptive correction of a beam passing through a patch of atmospheric turbulence.



Note: $\theta_1 < \theta_0$, $\theta_2 > \theta_0$, where θ_0 is the isoplanatic angle.

Figure 5. Adaptive Compensation and Isoplanatism

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8 One distinguishes between Yura's *lateral* coherence length ρ_0 and Fried's *transverse* coherence length r_0, where $r_0 = 2.1\ \rho_0$. See Section 3.6.

Because atmospheric turbulence exists in horizontally stratified layers of relatively small thickness, d ~ 0.1-1 km, (cf. Fig. 3), Section 3.3 points out that the actual path length through such a layer is a function of the viewing or elevation angle α above the horizontal (cf. Fig. 1).

Section 3.4 distinguishes between near-field and far-field conditions. In the near field, the light beam must be analyzed as a spherical wave, while in the far field it is described as a plane wave; the analysis in these two cases is somewhat different. For visible radiation from a transmitter of diameter D = 1 m, it is appropriate to use near-field conditions for ranges less than 2000 km, and far-field conditions (i.e., plane wave) at greater ranges.

Section 3.5 points out that the standard treatment of optical turbulence applies to the case when the fluctuation ΔA in the amplitude A of the laser beam is small, so that this can be treated by perturbation theory. If $\Delta A/A > 1$, which is often the case here, we do not know how to treat the problem in any general sense, except perhaps numerically.

When a narrow laser beam passes through a region of turbulence it will be deviated and also broadened from its initial state. These effects are discussed separately in Section 3.6 ("beam wander") and Section 3.7 ("beam broadening"). Some results for the beam broadening (also described as "beam spreading") from a source of diameter D under the condition that $D \gg r_0$, the coherence length, are presented in Section 3.8, and the optical turbulence analysis is summed up in Section 3.9.

For propagation over horizontal paths of less than approximately 100 km in length in the upper troposphere/tropopause/stratosphere region, it is expected that the beam wander would be very small (5-20 cm) regardless of wavelength. However, for paths of the order of several hundreds of kilometers, the wander is of the order of meters, which is significant. The beam broadening would also be small for paths less than 100 km, but for longer paths it too becomes of the order of meters. The calculations show that for near-horizontal paths of the order of tens of kilometers, turbulence phase effects are less that for vertical propagation from ground up to space. An additional very significant turbulence effect along these very long paths would be turbulence amplitude effects (i.e., scintillation) which are of the same order or more than for the vertical propagation case. Section 3.9 includes a discussion of tracking a moving target, which involves considerations of isoplanatism, or how to correct the laser beam by adaptive optics, a subject which is taken up in Section 4 below.

Adaptive compensation is achieved by a deformable mirror at the transmitter T whose shape changes in response to a sampling beam TS_1 that passes through the same patch of turbulence as the high-power beam TH. Path TS_1 is sufficiently close to TH because θ_1 is sufficiently small. However, path TS_2, where $\theta_2 > \theta_o$, the *isoplanatic angle*, is not sufficiently close to path TH and thus it is impossible to use a beam TS_2 to correct adaptively for path TH. Thus, paths TH and TS_1 are isoplanatic, but TS_2 is not isoplanatic with TH or TS_1.

3.2 THE PARAMETER C_n^2

Atmospheric turbulence is fundamentally a flow state characterized by a fluctuating or chaotic wind field. The fluctuating or swirling winds in turn result in fluctuations in other atmospheric constituents or parameters. Of special importance to optical propagation is the fluctuation in the density field, which results in the fluctuation in the refractive index field. This latter phenomenon is known as optical turbulence.

The atmospheric turbulence fluctuations have scale sizes that range from centimeters (or less) to tens of meters (or more). This range is the scale of laser beams, thus the central importance of turbulence to the description of laser beam propagation through the atmosphere. The statistical approach used to describe optical turbulence is that of *structure functions*. The *refractive index structure function* $D_n(r)$ describes the mean square difference between the refractive index, n, at two points separated by a distance r and is given by

$$D_n(r) = \langle[n(\mathbf{r_o} + r) - n(\mathbf{r_o})]^2\rangle \quad . \tag{1}$$

For homogeneous and isotropic turbulence, the structure function depends only on the magnitude of r and not on the vector $\mathbf{r_o}$, and this was assumed in this equation. The appropriateness of the structure function for describing laser propagation is evident since it measures the refractive index difference, and hence the phase difference across the wavefront. It was first shown by Kolmogorov in 1941 that there exists a range of scales called the inertial range where the turbulence cascade process dominates and yields a simple power law

$$D_n(r) = C_n^2\, r^{2/3} \quad . \tag{2}$$

The parameter, written by convention as C_n^2, is simply the constant of proportionality. The inertial range is the scale referred to earlier, that is, from centimeters to tens of meters. This parameter C_n^2 is the central parameter in describing turbulence effects, such as beam

broadening, beam wander, loss of coherence, and scintillation. These effects are calculated as integrals of C_n^2 along the propagation path. This formulation shows that knowledge of the variation in refractive index along the propagation path is critical to describing the wavefront distortions resulting from the optical turbulence.

Figure 3 demonstrates that turbulence in the free atmosphere is highly stratified, occurring in thin layers: the parameter C_n^2 shows large variations (factors of 100 or more) over these layers. These prominent characteristics are apparent in Fig. 3. Note that there are C_n^2 peaks of about 10^{-16} ($m^{-2/3}$) in the troposphere, as well as regions where C_n^2 is about 10^{-18}. The layers of turbulence are of the order of a hundred meters in the vertical direction, but are believed to be of the order of kilometers in the horizontal direction. This issue is further complicated by the intermittency of turbulence within a layer. That is, within a layer of "homogeneous" turbulence there are pockets of strong and weak turbulence.

We need to provide order of magnitude estimates for C_n^2. It is assumed that the aircraft is in the upper troposphere, at an altitude of 10 to 15 km: at midlatitudes this region includes the tropopause. Figures 6 and 7 show models of average C_n^2 profiles that are in widespread use. These profiles have been derived by averaging a number of measurements *so that the stratification of turbulence shown in* Fig. 3 is absent from the averages. The SLC and GL models both come from data taken at the same location (Maui) and can be considered as providing average profiles for a subtropical atmosphere.[9] From the GL-AMOS model, we see that 10^{-17} is a reasonable estimate of average C_n^2 for altitudes from 5 to 15 km in a subtropical atmosphere. Another model shown in the figures is the Hufnagel-Valley model (HV), which applies to a midlatitude atmosphere. This model has a lower tropopause (about 10 km) than the AMOS model (15-17 km). Therefore, there is more turbulence in the 7-15-km region than the AMOS models give--at 10 km, C_n^2 is about 3×10^{-17}.

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[9] The GL model is superior, as it is based on higher resolution data over a greater altitude range. However, it is only good at night. There are no high-resolution data on turbulence in the daytime, one area in which measurements are needed.

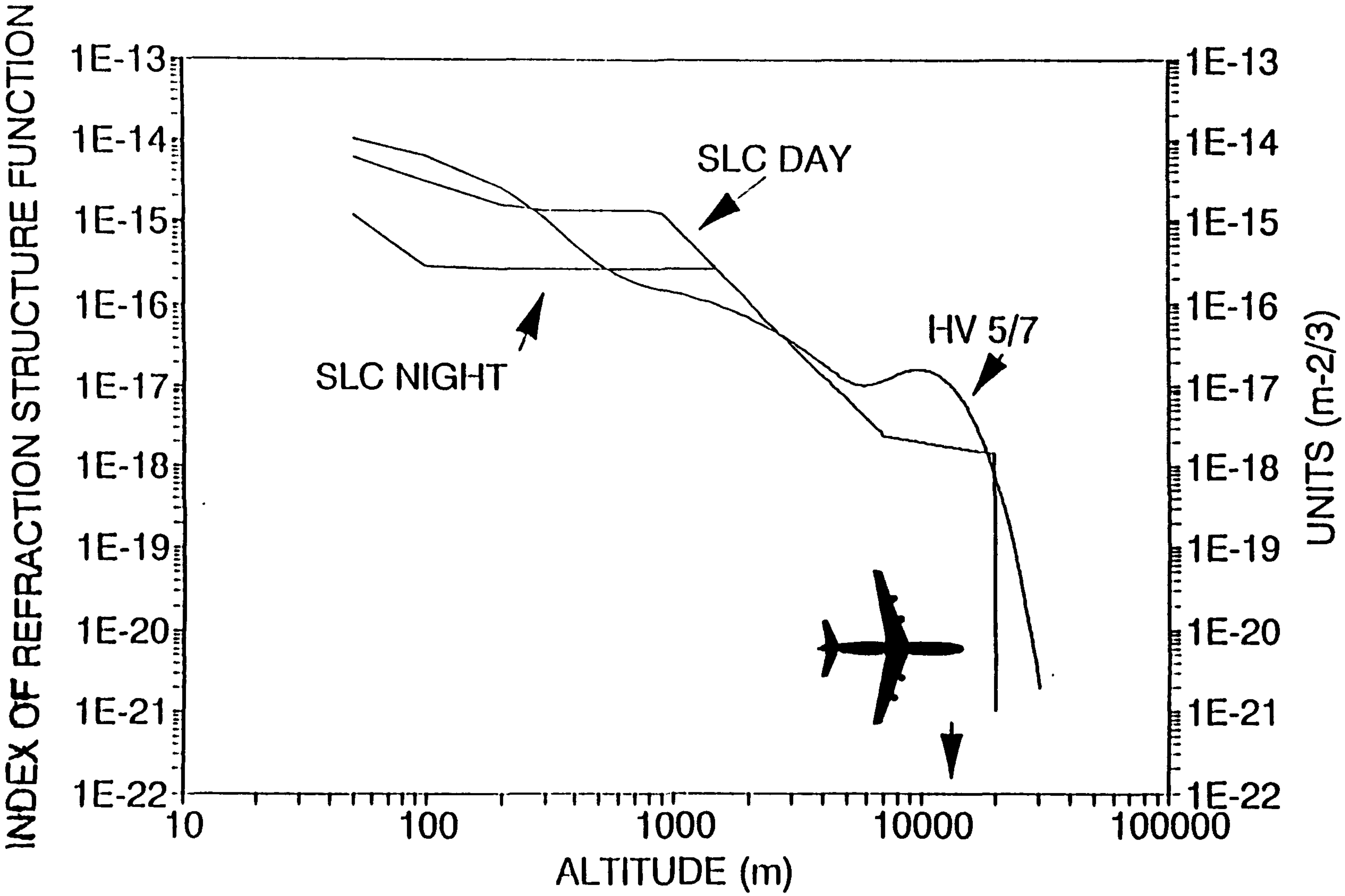

Figure 6. Comparison of SLC Day and Night and HV 5/7 Models
(Source: M. Tavis, Aerospace Corp.)

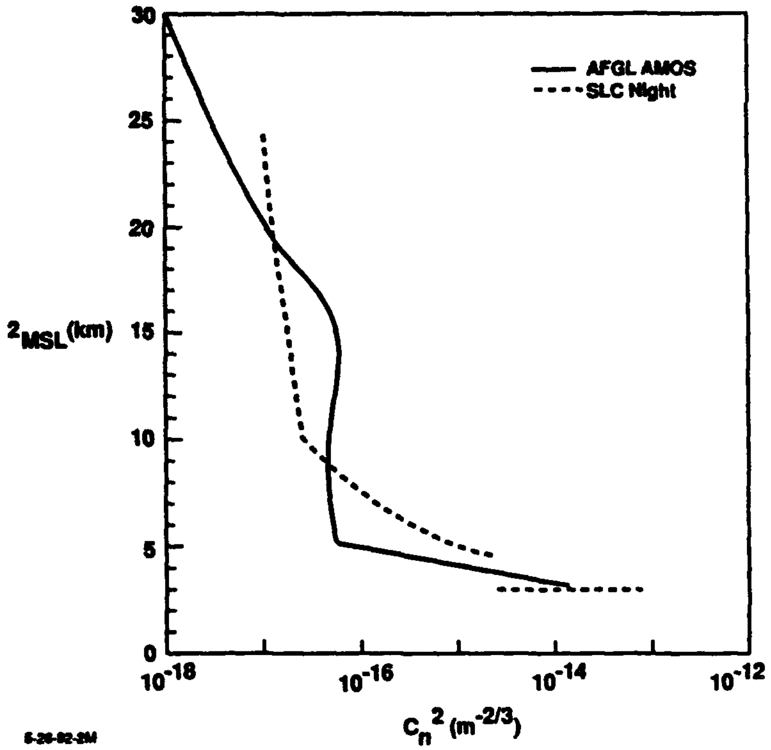

Figure 7. Comparison of the SLC Night and AFGL AMOS Models, Both Displayed Relative to the Mountaintop Surface

An analysis by the Aerospace Corporation (Tavis, 1991) finds that two commonly used models (SLC and HV 5/7) of the atmospheric optical turbulence parameter C_n^2 give significantly different results in describing the effects of turbulence on beam propagation. The models vary so much because in past applications to vertical "seeing" through the atmosphere the entire ground-to-space path was of interest, and now it is a little tail at the end of the distribution. Even an order of magnitude variation in this region had little effect on previous calculations, but now this region is dominant. Indeed, there is no experimental data available on the overall optical turbulence along near-horizontal high-altitude long-range paths, and a substantial effort (probably using two aircraft, or else one aircraft and a balloon target) is required to obtain the large amounts of data that are needed.

It is expected that propagation over long, near-horizontal paths (hundreds of kilometers) through the troposphere would involve propagation through regions with a wide disparity in turbulence. The models shown in Fig. 5 are derived by averaging a number of measurements, that is, at a given altitude the model value represents an average where a layer is or is not present. For the propagation scenario it is appropriate to use the average value over the entire path. This assumption of homogeneous turbulence along the

path is not physically realistic, but it should not be important for the properties (such as plane wave coherence) which depend only on the integrated turbulence. Other effects such as scintillation and isoplanatism depend on the distribution of turbulence along the path. Since there is very little data on turbulence or laser propagation along horizontal paths in the stratosphere, the assumption of constant turbulence is made here, in absence of anything better. In all that follows, it is assumed that C_n^2 is 10^{-17} along the entire path.

Of course, a more thorough simulation would use a model profile with altitude variation in C_n^2. In addition, the curvature of the earth should be included in modeling the variation of turbulence along the propagation path. For the example of an aircraft at 12.5-km and target at 25-km altitude, at 400-km range, the earth's curvature results in the laser being pointed at an angle of 90 degrees from the vertical. These are refinements that must be included in the full-system simulation and study. The intent here, however, is to outline some of the issues that arise from propagation through turbulence and to give order of magnitude estimates of these. For these purposes, the assumption of constant C_n^2 along the path is adequate. A less severe propagation scenario is represented by using a constant value of 10^{-18} along the path. The effect of using this value can be represented by scaling the results appropriately from our more severe value of 10^{-17}.

3.3 GEOMETRICAL CONSIDERATIONS

If the laser beam looks upward at an angle α above the horizontal, the maximum path length L in a turbulent layer of thickness d is

$$L = d/\sin \alpha \quad . \tag{3}$$

Some "representative" numerical values for α are listed in Table 1, and thus from Table 5 one sees that L can be in the range 1 to 5 km for d = 0.1 km. (Note that on account of the curvature of the earth the maximum path length within a layer of thickness d = 0.1 km is 36 km, which corresponds to $\alpha = 0.16°$.)

Table 5. Effective Path Lengths Through Turbulence as A Function of Elevation Angle α (d = 0.1 km)

α(°)	0.1	1	2	5	10	20
$L = d/\sin\alpha$	57	5.7	2.9	1.1	0.58	0.29

3.4 NEAR-FIELD VS. FAR-FIELD CONDITIONS

The propagation of a *collimated laser beam* through turbulence can be treated to first order as *plane wave propagation*, and a *focused beam* in terms of *spherical waves*. Explicitly, the case of a collimated beam or plane wave propagation applies to the *far field* situation, i.e.,

$$\text{range} > D^2/\lambda \quad , \tag{4}$$

while the case of a focused beam corresponds to the opposite, *near-field* situation. For definiteness, we shall consider a mirror with an optical aperture D = 1 m, and a laser wavelength range of 0.5 to 10 μm, and $C_n^2 = 10^{-17}$. Thus D^2/λ = 2,000 km for λ = 0.5 μm or 100 km for λ = 10 μm.

3.5 WEAK FLUCTUATIONS

A key question to ask is whether the assumption of weak fluctuations applies. This is usually stated in terms of the variance of log amplitude. For a plane wave the variance of log amplitude is given by the Rytov parameter

$$\sigma_\chi^2(L) = 0.31\ k^{7/6}\ L^{11/6}\ C_n^2 \quad , \tag{5}$$

where $k = 2\pi/\lambda$ and C_n^2 is assumed constant along the path of effective length L. Weak fluctuation theory applies provided $\sigma_\chi^2 < 0.25\text{-}0.3$. Table 6 shows values for a plane wave that result from assuming $C_n^2 = 10^{-17}$; for a spherical wave, $\sigma_\chi^2(L)$ is smaller by a factor 0.4.

Table 6. Variance of Log Amplitude

L (km)	σ_χ^2, λ = 0.5 μm	σ_χ^2, λ = 1 μm	σ_χ^2, λ = 10 μm
10	0.01	0.0057	3.9×10^{-4}
50	0.24	0.109	7.4×10^{-3}
100	0.87	0.38	0.026
500	17	7.5	0.51
1000	60	27	1.8

These numbers show that weak fluctuation theory fails for all 500-km paths, regardless of wavelength. Since the variance is linear in C_n^2, an increase in turbulence above 10^{-17} would bring the issue of validity of weak fluctuation theory into question at shorter paths. These simple calculations show that an airborne laser may be operating in the region where the applicability of weak fluctuation theory is in question. In strong turbulence, scintillations saturate and the beam breaks up into smaller spots. Experiments would clarify this question. There is no complete propagation theory for anything other than the weak fluctuation case. The strong fluctuation case should be an active research topic; it is a very difficult problem.

D.P. Greenwood (in review) makes the following points:

> Unfortunately, no one has developed detailed theories describing the behavior of phase when intensity fluctuations saturate, which is the real problem at hand. But our wave optics codes work admirably in this regime. They are not affected by "saturation" in that these codes propagate in a step-wise fashion. We should have little difficulty predicting propagation and adaptive-optics performance with our codes, except that we are limited in our knowledge of the upper atmospheric turbulence. This is not to say that it will be easy, however, as the strong scintillation will have significant hardware implications, implications which must be addressed in the codes.

With these caveats, the beam parameters can be calculated for the weak fluctuation case. If we consider the average effect of turbulence on the propagation of a single pulse, the classical effects of concern are *scintillation*, *beam wander*, and *beam broadening*. Scintillation refers to the fluctuations of the on-axis beam intensity. The normalized intensity variance is given by $\sigma_I = 2\sigma_\chi$. If $\sigma_\chi = 0.1$, then the on-axis intensity has 20 percent fluctuations in intensity since $\sigma_I = 0.2$. The fact that χ is a Gaussian variable allows statistics to be used. The previous Table 6 shows values for the intensity fluctuations. Only those theoretical values less than about 0.3 should be regarded as predictive of experimental scintillation; higher values suggest saturation of scintillation.

3.6 BEAM WANDER

To calculate the beam wander effects, it is assumed that a 1-m beam emerges from the transmitter. The variance of the beam wander is given by

$$\langle \rho_c^2 \rangle = 2.97\, L^2\, D^{-1/3} \int_0^L C_n^2(\eta)\, d\eta \qquad (6)$$

where η = distance along the optical path through the layer of turbulence (whose length is L) (see, e.g., Ishimaru, 1978b; some authors use a somewhat different numerical constant). For constant turbulence, this is

$$<\rho_c^2> = 2.97\, L^3 D^{-1/3} C_n^2 \quad . \tag{7}$$

Note that there is no variation with wavelength. Closely related to this is the mean square angle of arrival. This latter is derived from the broadening by dividing by L^2. The RMS beam wander for a 1–m beam is very small: for L = 1 km, the RMS wander is 170 μm; for 10 km, 0.55 cm; for 100 km, 17 cm; for 500 km, 1.9 m; for 1000 km, 5.5 m. For the RMS angle of arrival fluctuation, these correspond respectively to 0.17, 0·55, 1.7, 3.8, and 5.5 μrad. As these figures suggest, the wander may be a significant problem for paths longer than 100 km.

3.7 BEAM BROADENING

The beam broadening is calculated from the expression

$$<\rho_s^2>= 4L^2/(k\, D)^2 + (D/2)^2\{1-L/f\}^2 + 4L^2/(k\, \rho_o)^2\, [1 - 0.62\, (\rho_o/D)^{1/3}]^{6/5} \quad , \tag{8}$$

where f is the beam focus distance and ρ_o is Yura's lateral coherence length given for a spherical wave (focused beam case) as

$$\rho_o = \{1.46\, k^2 \int_0^L C_n^2(\eta)\, (1-\eta/L)^{5/3}\, d\eta\}^{-3.5} \quad . \tag{9}$$

Fried's transverse coherence length, denoted by ρ_o, is more widely used that ρ_o, but the latter was historically used in the beam width expressions. The two are simply related by $r_o = 2.1\, \rho_o$.

Strictly, expression (8) applies only to the case where the transmitter diameter $D >> \rho_o$, a condition that will be satisfied in the TMD scenario. Note that the first term in Eq. (8) for <rs2> is due to diffraction, the second is the collimated or focused beam radius and the last term is the turbulence spreading. For the plane wave case, the altitude weighting function of the integrand in ρ_o is omitted. For a constant C_n^2, the spherical wave form produces

$$\rho_o = \{1.46\, k^2\, C_n^2\, 3L/8\}^{-3/5} \quad . \tag{10}$$

The factor 3/8 is omitted for the plane wave case. Table 7 gives values for ρ_o for various path lengths and wavelengths.

For comparison purposes, plane wave ρ_o for vertical propagation from the ground up to space is typically 2.5-5 cm. Thus, there is a comparable integrated turbulence through the entire atmosphere as a horizontal 100-km path through a C_n^2 of 10^{-17}. For longer paths, the turbulence is more severe than ground-to-space.

Table 7. Values for the Lateral Coherence Length ρ_0 (m)

L (km)	$\lambda = 0.5\,\mu m$		$\lambda = 1\,\mu m$		$\lambda = 10\,\mu m$	
	plane	spherical	plane	spherical	plane	spherical
1	0.66	1.18	1.39	2.5	24.0	43
10	0.16	0.29	0.35	0.63	5.8	11
100	0.04	0.075	0.088	0.11	1.5	2.7
500	0.015	0.026	0.033	0.06	0.53	0.96
1000	0.0096	0.017	0.022	0.04	0.35	0.63

3.8 SOME RESULTS

For a 1-m diameter mirror and using the previous values of ρ_0, the beam broadening (or spreading) can be calculated. Table 8 shows the results for the RMS beam radius ρ_s (note that some authors use the plane wave ρ_0 for both the focused and the collimated case, while here in Table 8 we use the spherical form for the focused case).

Table 8. Values for RMS Beam Radius ρ_s (m)

L (km)	$\lambda = 0.5\,\mu m$		$\lambda = 1\,\mu m$		$\lambda = 10\,\mu m$	
	collimated	focused	collimated	focused	collimated	focused
1	0.50	0.0002	0.50	0.0003	0.50	0.003
10	0.50	0.0043	0.50	0.0045	0.50	0.031
100	0.61	0.18	0.58	0.16	0.60	0.32
500	4.8	2.7	4.2	2.3	2.6	1.8
1000	16	8.4	13	6.9	7.2	4.5

In the 10-µm case, the broadening effects are almost entirely due to diffraction for paths less than about 100 km. This is expected, since turbulent effects become prominent when the coherence length is of the same order as the transmitter diameter, turbulence dominates when $\rho_0 < D$. As can be seen from Table 8, turbulence broadening is a significant problem for any wavelength along paths longer than 100 km.

M. Tavis, 1991, has done some computations for laser beam propagation from an aircraft at 13 km to a target at 20-km altitude and at a range of 250 km and 500 km. He computes the Strehl Ratio

$$St = \frac{\text{Peak intensity received at target in presence of turbulence}}{\text{Intensity that would be received if there were only spreading by diffraction}} , \quad (11)$$

and is shown in Fig. 8, where he finds that two commonly used models for the optical turbulence parameter C_n^2 [SLC (Submarine Laser Communication) and HV (Hufnagel-Valley) 5/7) give significantly different results. Explicitly, the SLC model predicts values of St which suggest that adaptive optical compensation would not be needed, whereas the HV model gives so much smaller values of St that adaptive compensation is clearly necessary. The implications of this calculation are evidently significant, suggesting that the value of St and thus the quality of the beam may depend critically on the details of the atmospheric turbulence.

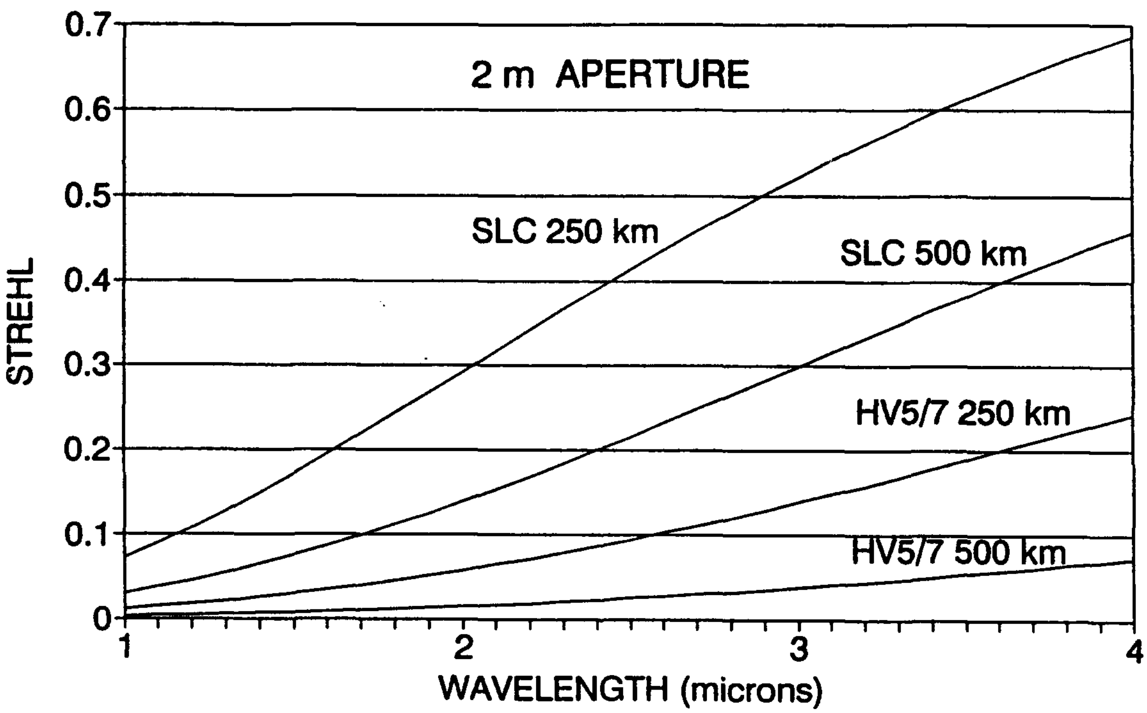

Figure 8. Atmospheric Turbulence Strehl Ratio for Aircraft at 13 km and Target at 20 km, for SLC and HV 5/7 Models (from M. Tavis, 1991)

3.9 SUMMARY

These calculations can be summarized as follows. For propagation over horizontal paths of less than approximately 100 km in length in the upper troposphere/tropopause/ stratosphere region, it is expected that the beam wander would be very small (5-20 cm) regardless of wavelength. However, for paths of the order of several hundreds of kilometers, the wander is of the order of meters, which is significant. The beam broadening would also be small for paths less than 100 km, but for longer paths it too becomes of the order of meters. An additional very significant turbulence effect along these very long paths would be scintillation.

The calculations show that for near-horizontal paths of the order of tens of kilometers, turbulence phase effects are less that for vertical propagation from ground up to space. Turbulence amplitude effects (i.e., scintillation) are of the same order or more than for the vertical propagation case. The difference between these comparisons is a consequence of the path weighting. These statements are made assuming homogeneous turbulence along the path which is an appropriate first order approximation. The horizontal or near-horizontal paths would have their own peculiar problems. For example, the isoplanatic angle (defined in Section 3.1 and Fig. 5) would typically be smaller than for the vertical case due to the path weighting. These statements are made assuming homogeneous turbulence along the path which is an appropriate first order approximation. The horizontal or near-horizontal paths would have their own peculiar problems. For example, the isoplanatic angle defined by

$$\theta_0 = \{2.91\, k^2 \int_0^L C_n^2(\eta)\, \eta^{5/3}\, d\eta\}^{-3/5} \tag{12}$$

would typically be smaller than in the vertical case due to the path weighting. Typical values of θ_0 for vertical propagation at 1 μm are about 15-20 μrad. For 1 μm, horizontal propagation gives isoplanatic angle of the order of 1 μrad at 100 km and as small as 0.03 μrad at 1000 km. This would mean that the isoplanatic patches would be small and the operation and use of adaptive optics unproductive.

To clarify this concern about isoplanatism, a simple argument can be given. Assume that the target cooperates to the extent that it provides a beacon. Let c be the speed of light and V_m the target speed (effective speed, including aircraft, transverse the line of sight). In the time it takes for light to propagate from the target to the adaptive optics and back, the target has moved. It is simple to show that the target has moved through an angle θ given by $2V_m/c$. This look-ahead angle θ, for a representative value of V_m of 1 km/sec,

is calculated to be 6.7 μrad. The turbulence isoplanatic angle, θ_o, gives the maximum angular (or isoplanatic) patch for which turbulence can be regarded as the same. In more practical terms, if the phase distortions are measured along one direction, θ_o gives the maximum look-ahead angle for which the outgoing path can be treated as having the same distortions as the beacon. It is clear that in the TMD scenario, the look-ahead angle will be significantly greater than the isoplanatic angle, and adaptive optics performance in this scenario will be degraded. Specifically, the degradation of the Strehl ratio for a look-ahead angle θ is given by $\exp[-(\theta/\theta_o)^{5/3}]$. The scenario described where the target provides a beacon is also applicable to the case where a glint from a tracking beam on the target is used to provide the beacon. In general, this issue must be dealt with in any case where the path of sensing differs from the path of the HEL beam.

The formulation of the look-ahead problem and isoplanatism is the traditional one for adaptive optics systems. A critical part of this formulation is that the beacon point and the aim point are the same point on the moving target. An alternative approach has been proposed to avoid these problems. Namely, the beacon and aim points are no longer the same target point. Thus, the beacon ideally comes from illumination of the tip of the target while the aim point is another part of the target body. For such a system the Strehl ratio given above does not apply. However, problems associated with isoplanatic angle still arise.

Another concern in the area of adaptive optics arises from the high slew rates in TMD. The slewing of the laser beam (at a rate of V_m/L where L is the target distance) would set severe constraints on the bandwidth requirements of the adaptive optics system. Specifically, the Greenwood frequency fg provides this requirement and it is calculated from (see Greenwood, 1977)

$$f_g = \{0.102k^2 \int_0^L C_n^2(\eta)\, v_e(\eta)^{5/3}\, d\eta\}^{3/5} \quad , \tag{13}$$

where v_e is the effective wind speed transverse to the beam and, as in Eq.(6) or (12), η is the coordinate along the optical path within the region of turbulence. v_e takes into account the slewing of the beam due to the aircraft and target motion. For the approximation where the missile speed is much larger than the winds or the aircraft speed transverse to the path, the above equation reduces to the following, for homogeneous turbulence:

$$f_g = V_m\, \{0.038\, k^2\, C_n^2\, L\}^{3/5} \quad . \tag{14}$$

For 1 μm wavelength, $C_n^2 = 10^{-17}$, and a path length L = 100 km, $f_g = 1.27\ v_m$. Thus, even for the low estimate of missile speed of 100 m/sec, f_g = 127 Hz, while for the more

realistic value of 1 km/sec, f_g = 1270 Hz. For longer paths, these numbers grow correspondingly. Values of Greenwood frequency of hundreds of Hz present problems to today's adaptive optics technology. These estimates show that even for the most optimistic case, the slewing would present problems. Strictly speaking, the aircraft speed transverse to the beam as well as the transverse windspeed should be included. These refinements in the calculations would not change the conclusions.

These calculations are made from weak fluctuation theory, and it has been shown that there is reason to question the applicability of this approach in the strong fluctuation domain that applies to paths longer than approximately 100 km. There are no simple formulas to apply with confidence. In such strong turbulence, the concepts of "beam" and "focus" are difficult to maintain, since the beam is broken up into smaller beams. This is a central problem which has not yet been solved.

4. ADAPTIVE CORRECTION FOR TURBULENCE

The preceding discussion points out that at ranges in excess of 100 km there is significant turbulent dispersion of a HEL beam. The normal way to correct for this is to sense the target with the laser beam (or with an auxiliary beam) and then correct the shape of the transmitting mirror to compensate for the turbulent dispersion. This procedure can be used if the angular variation in the direction of the received target, $\Delta\psi$, is much less than the isoplanatic angle θ_o, which characterizes the atmospheric turbulence along the given path. Here $\theta_o \sim 1$ μrad or less, cf. Section 3.10.

Reference to Fig. 1 shows that if the path angle is a and the target velocity is V_m, then the relevant travel time of the light beam is 2 P_1/c (c = velocity of light[10]), and thus

$$\Delta\psi = V_m \sin\alpha \, (2R_1/c)/R_1 = 2 \sin\alpha \, (V_m/c) \quad . \tag{15}$$

Some representative ballistic missile burnout velocities are listed in Table 1; taking $\alpha = 3°$, $V_m = 2$, 4 km/sec gives $\Delta\psi = 0.7$, 1.4 μrad respectively, which is larger than the isoplanatic angle θ_o for ranges much in excess of 100 km, so that the "normal" adaptive correction scheme does not apply for the very long ranges that are of real interest here.

USAF Phillips Laboratory has been addressing these problems for some time (see, e.g., Fugate et al., 1991; Gates and Ellerbroek, 1991), and has suggested a potential method for correcting the deleterious effects of atmospheric turbulence on laser propagation. The technique involves transmitting an illuminator beam whose center is positioned just in front of the nose of the target. The return reflected from this illuminator becomes a beacon which would sample the turbulent atmosphere and provide the phase information with which to transmit the laser weapon. There are several problems associated with this technique. First, the illuminator spot would be quite large, several times the isoplanatic angle in size. This means that the return signal would be a mix of atmospheric paths about the correct one needed for the laser weapon, and this would introduce errors in the potential correction. It is hoped that symmetry would cancel out

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10 For R_1 = 100-1000 km, 2 R_1/c = 0.3-3 msec, or the adaptive mirror would have to respond at frequencies up to 300-3000 Hz. Mirrors operating at frequencies significantly greater than 1 kHz have been built.

some of this error. Second, jitter would move the illuminator around, causing a tilt error for the correct laser weapon beam. By aiming the illuminator ahead of the target it is hoped that the brightest return would be from the nose of the target, and that this jitter error would be minimal.[11] Finally, the degradation of the illuminator due to atmospheric propagation would be manifested as a nonuniform beacon (speckle) which could also lead to significant correction error. It is hoped that the use of a large aperture to transmit the illuminator beam and the use of multiple wavelengths will ameliorate this problem. For related work at MIT/Lincoln Laboratory (LL), see, e.g., Primmerman et al., 1991.

However, both USAF Phillips Laboratory and MIT/LL have been working on ground-to-space propagation, involving both cooperative and uncooperative targets. The adaptive optics technology so developed has clear applicability, but there are new problems of physics and technology as well. In particular, while some calculations have been done on long-horizontal-path propagation at high altitude and to postulate how well the beam might propagate with and without adaptive correction, no experimental work has yet been done in this area.

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[11] The MIT/LL concept of the illuminator has a separate beam over-filling the target, so that any motion of that beam would not be sensed by the tracker system.

5. OTHER CONCERNS

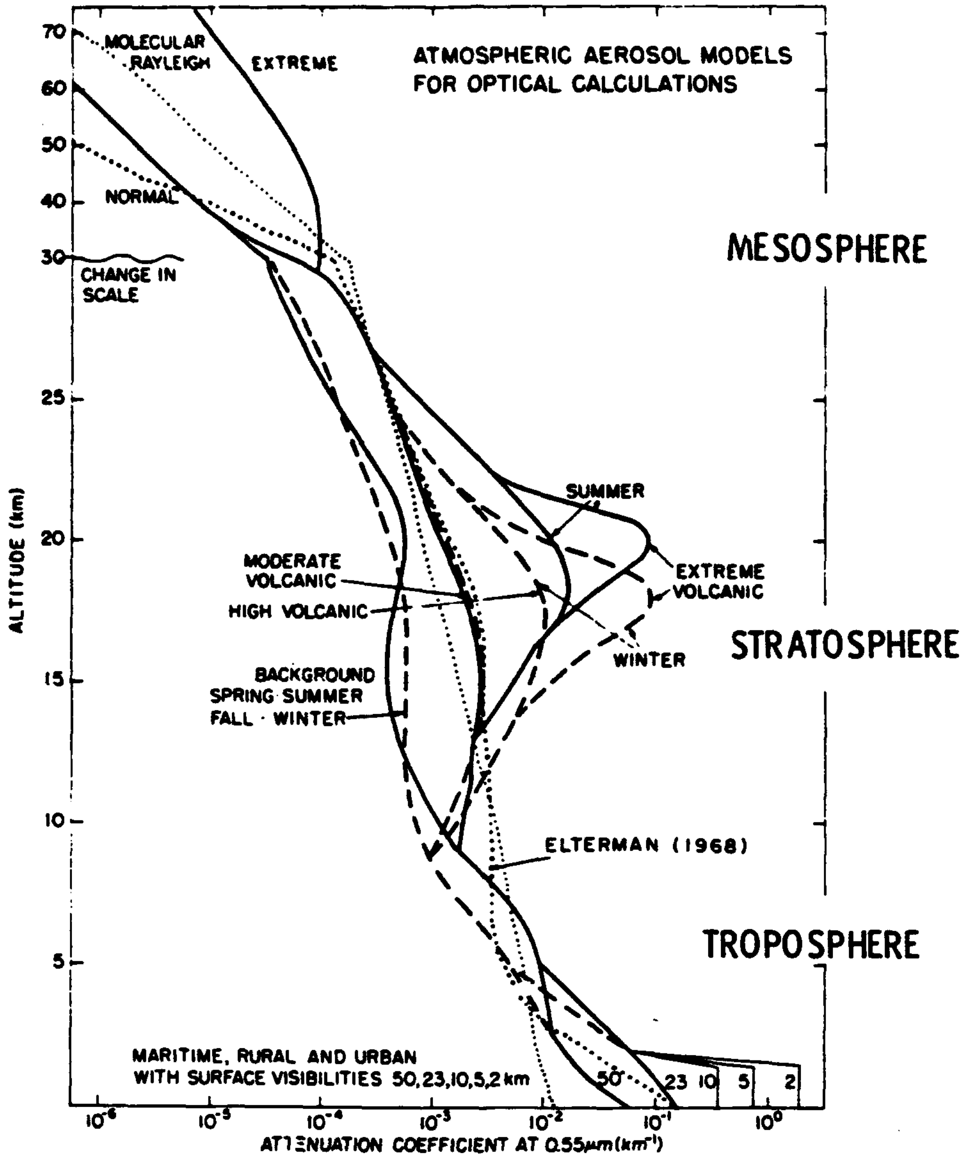
5.1 THERMAL BLOOMING

There are other atmospheric effects that could be important. If the HEL beam is not slewed sufficiently rapidly, the absorption along the path could be important, as it provides the mechanism for thermal blooming.[12] Aerosol absorption has usually been considered the critical mechanism in High-Energy Laser (HEL) thermal blooming studies (at 1 μm). In the ground-to-space scenario, the significant thermal blooming occurs in the lower atmosphere [Planetary Boundary Layer (PBL) lowest 1-2 km of atmosphere] where there is a significant concentration of aerosols that absorb the beam energy. Figure 9 shows the aerosol extinction (= absorption + scattering) profiles that correspond to the various models. As can be seen, the dominant contribution arises from the PBL. Note, however, that all the various models show a peak in the vicinity of the tropopause and lower stratosphere arising from volcanic aerosols. The moderate volcanic model extinction at the tropopause is about a factor of 100 less than in the PBL. For propagation through long horizontal paths through this region, the optical depth would be greater than that for vertical propagation. This would result in significant absorption and thermal blooming. In contrast to the ground-to-space scenario where the significant blooming arises in a limited spatial region of the PBL, the blooming over long tropopause paths would be more distributed. As thermal blooming is not a threshold effect but arises due to atmospheric heating from absorption, it might be expected that the distributed absorption would result in a gradual, distributed blooming of the laser beam. A critical factor in assessing the importance of blooming is the effective wind or slew rate. In the TMD scenario, the slew rates may be high enough that blooming would not be a problem. If this is the case, the sole effect of the absorption would be a significant attenuation of the beam.

MIT/LL have investigated both aerosol and molecular thermal blooming and consider the mechanism to be well understood and not an insuperable problem. Dr. Jan Herrmann, MIT/LL, has done propagation calculations on the molecular and aerosol

[12] For a review, see, e.g., APS, 1987, Section 5.4.8.

absorption for 300-km path lengths at 12.5-km altitude. At 3.8 μm (DF) the radiance decreases by a factor of three (Strehl Ratio 0.3), but at 1.06 μm the effect is negligible.



The vertical distribution of the aerosol extinction (at 0.55 microns) for the different models. Also shown for comparison are the Rayleigh profile (dotted line) and Elterman's [1968] model. Between 2 and 30 km, where a distinction on a seasonal basis is made, the spring-summer conditions are indicated with a solid line and fall-winter conditions are indicated by a dashed line.

Figure 9. Aerosol Extinction Profile in the Atmosphere (Source: Jursa, 1985, p. 18-14)

5.2 DUCTING

The tropopause region is one of high thermal gradients, which imply high gradients in the refractive index. The same is true in the lower stratosphere, although to a lesser extent. Figure 10 shows a sample temperature profile from a subtropical atmosphere (Maui). For near-horizontal propagation, these gradients may present problems, specifically a ducting effect that may result in blind spots. Furthermore, these temperature inversions are not static; like everything else in the atmosphere, the inversions are subject to oscillations arising from buoyancy or gravity waves. These oscillations are over long spatial and temporal scales. The temporal oscillations would result in slow oscillations of the blind spots, and the spatial structure of the temperature inversion layers would also result in oscillations due to the aircraft motions. There are very few data on the fine scale spatial and temporal structure of the temperature inversions in the upper troposphere, tropopause region, and lower stratosphere; such data are needed to ascertain the importance of ducting.

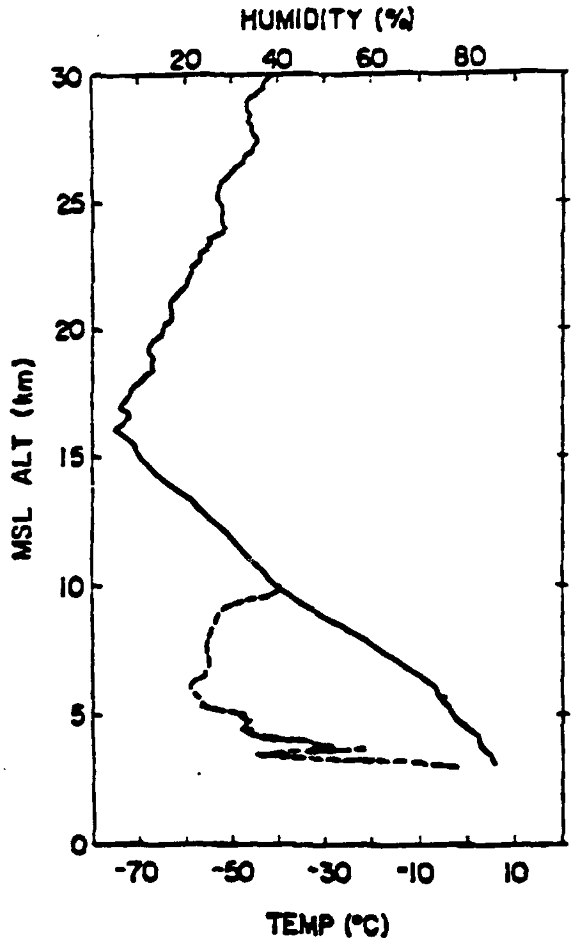


Figure 10. Sample Temperature Profile in a Subtropical Atmosphere Showing High Thermal Gradients

6. SUGGESTED MEASUREMENT AND STUDY PROGRAM

6.1 CLOUDS

If an airborne laser (ABL) program is contemplated for the present kind of application, it is clear that we require a detailed understanding of cloudiness and in particular cloud-free-lines-of-sight in long near-horizontal paths for high-altitude flight regimes, say 12-17 km (39-56 kft). It must be stressed that our knowledge of high-altitude cirrus and in particular of subvisual cirrus is rather limited, and there is no substantial data base on PCFLOS in long-distance near-horizontal paths, because there has been little need except for long-range air-to-air Infrared Search and Track (IRST) applications. Apart from any available IRST data, the best data base is probably provided by the NASA SAM and SAGE limb-viewing satellite (cf. Bauer, 1990, Section 7.5.4).

6.2 OPTICAL TURBULENCE

Radars and stellar scintillometers are currently the only available methods for range-resolved, remotely-sensed C_n^2 measurements in the lower stratosphere. Stellar scintillometers have very poor vertical resolution and are incapable of resolving the layering or stratification of turbulence.

The present data base for C_n^2 is both inadequate and critical for the present application: thus the analysis of Tavis, 1991, illustrated in Fig. 7, finds that the difference between the SLC and the HV 5/7 models is so large that one suggests that Adaptive Optics is necessary for the present application, while the other one suggests that it is not. It is thus clear that a climatological data base for C_n^2 is needed, and it seems that the only way to obtain such a data base is by aircraft measurements, probably using one aircraft with a laser transmitter and a second aircraft as target. This would clearly be very expensive.[13]

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[13] Small jets (e.g., Learjet) can operate up to 51 kft, much higher than a KC-135, and are of course much cheaper to operate per flight hour, if they have an adequate payload. Unmanned vehicles may also be useful.

However, it appears that ground-based (radar or lidar) observations simply do not have the sensitivity needed for this very difficult measurement. Right now there exists a National Oceanic and Atmospheric Administration/Federal Aviation Administration (NOAA/FAA) network of 30 UHF Doppler radars (400 MHz) in the U.S. Midwest which is oriented towards tropospheric wind sensing, but does not have the power or resolution needed for the present application. There are a few high-power 50-MHz Doppler radars [Army Atmospheric Science Laboratory (AASL) at White Sands Missile Range (WSMR), NOAA at Flatlands, IL] that are capable of high vertical and temporal resolution in the 15-20-km region. These systems also have the ability to simultaneously measure winds. Since these are both existing facilities, if they could measure C_n^2 or some surrogate,[15] this could be done for several orders of magnitude lower cost than aircraft-based measurements. The measurement of the other parameters via ground-based systems (i.e., lidars) would require more powerful lidars than are normally used since the altitudes of interest have fairly weak backscatter due to the density, but this option should be pursued.

The ideal measurement system would involve a suite of instrumentation on an aircraft, including lidars, since paths of the same order as a TMD optical path could be characterized. Spatial resolution could be achieved that is higher than with ground-based systems, and the different quantities of importance could be measured in essentially the same volume.

Thus a suggested program of atmospheric measurements and propagation study needs might have the following components:

- Atmospheric Measurements for Optical Turbulence:
  - Path characterization for aerosols/extinction/absorption
  - Path characterization for turbulence layers
  - Path characterization for winds (thermal blooming/Greenwood frequency[16])
  - Path characterization for temperature inversion layers
  - Path characterization for clouds, especially cirrus.

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14 Small jets (e.g., Learjet) can operate up to 51 kft, much higher than a KC-135, and are of course much cheaper to operate per flight hour, if they have an adequate payload. Unmanned vehicles may also be useful.

15 Which does not appear to be likely.

16 See Section 3.8, Eq. (13, 14).

- Propagation Study Needs for Optical Turbulence:
  - Strong fluctuation theory for turbulence
  - Numerical wave-optics code studies for propagation through strong turbulence
  - Study of adaptive optics with small isoplanatic angles[17] from an aircraft
  - Study of atmospheric ducting.

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[17] See Fig. 5 and Eq. (12) in Section 3.8.

7. DISCUSSION

Environmental factors--both clouds and turbulence--can be a program stopper for ABL use for TMD, because at mid- and low latitudes conventional aircraft cannot fly high enough to avoid problems with clouds and (probably also) turbulence. Explicitly:

- In the tropics, cumulonimbus go so high that they would certainly have to be avoided; this may be feasible because of their relatively limited spatio-temporal extent.
- At midlatitudes, it may be possible to operate high enough with almost conventional aircraft, while at high latitudes "conventional" aircraft are probably adequate most of the time.

The discussion of turbulence points to several questions and problems. With regard to phase effects of coherence, beam wander, and broadening, one can demonstrate that a 100-km near-horizontal path at about 15-km altitude has effects of the same order as vertical propagation from ground to space, but longer paths are worse. For scintillation and isoplanatism, the near-horizontal path of 100 km is worse than a vertical ground-to-space path. Specifically, the long near-horizontal paths may violate the weak fluctuation condition, which is assumed to derive expressions for optical effects. This raises important questions about the validity of the estimates of turbulence effects. Additional questions and problems are raised in the specifications for adaptive optics or, specifically, isoplanatic angle and the required bandwidth. These questions arise because of the high slew rates required to track a TMD target.

Thus, if airborne lasers are contemplated for the present TMD application, a measurement program should be started now to gain a quantitative understanding of how serious the problem of clouds and turbulence is likely to be, so as to be able to make a decision on an ABL program some 2-3 years in the future based on a reasonably adequate "climatological" data base on atmospheric optical turbulence, in particular on the parameter C_n^2 as function of time of day, latitude, and season. As indicated in Section 5, such a measurement program should involve a coordinated program of air- and ground-based measurements.

Further, the problem of adaptive compensation for atmospheric turbulence as sketched in Section 4 could be significant, and might even be a "program stopper." An active program towards resolving this is under way at USAF Phillips Laboratory (cf. Fugate et al., 1991; Gates and Ellerbroek, 1991) and at MIT/Lincoln Laboratory[18] (cf. Primmerman et al., 1991). However, increased emphasis may well be necessary to resolve the problem.

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18 Work in progress by Dr. Jan Herrmann (MIT/LL) suggests that atmospheric compensation may not be necessary for the present application.

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